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ABSTRACT

This paper discusses the nature of cognitive research and its implications for learning and teaching science. In addition to needing adequate financial support, active involvement of scientists and educators, and education of teachers, two other factors should loom large in the development of new instructional materials in science and in the design of new instructional strategies. The first is cognitive research findings on teaching, learning, and problem solving. The second factor is the nature of science as it is practiced by scientists. The paper is divided into sections on research on learning and problem solving in science, lack of alignment between instructional practices and current views of learning, and factors necessary to bring about alignment between instructional practices and current views of learning. (Contains 115 references.) (MM)

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COGNITIVE ASPECTS OF LEARNING AND TEACHING SCIENCE

JOSE P. MESTRE

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Cognitive Aspects of Learning and Teaching Science

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Introduction

Imagine the following scenario:

> Heather, a very bright ninth grader, is asked to explain the mechanisms causing the seasons and the phases of the moon. She has not yet received any formal instruction on these topics in her ninth grade earth science class although these topics were covered in science lessons from earlier grades.
>
> During the course of her explanations, Heather displays some misconceptions. For example, she believes that the earth orbits the sun in a bizarre "curlicue" pattern (see Figure 1a) and that the seasons are caused by the proximity of the earth to the sun at different times during the orbit. She explains that when the earth is closest to the sun at point X in Figure 1a, it is winter in the northern hemisphere because the light rays from the sun hitting the earth are "indirect," and that when the earth is at point Y, it is summer because the light rays hitting the northern hemisphere are "direct." She goes on to explain that direct rays are those that originate from the sun and travel in a straight line to the earth and that indirect rays are rays that "bounce off" somewhere in space before reaching earth (see Figure 1b).
>
> In terms of explaining the phases of the moon, Heather believes that the shadow of the earth on the moon causes the phases.

This scenario is not fiction--it summarizes events that actually transpired during an interview in a school in Cambridge, Massachusetts, events that are well-documented in the educational video, *A Private Universe* (Pyramid Film & Video). Heather clearly has formed a mental representation that mixes both erroneous and correct ideas into a muddled package. The notion of direct and indirect light does explain the seasons, although this notion has nothing to do with her erroneous belief that the earth travels in a curlicue orbit and gets much closer to the sun during certain times of the year. Similarly, she inappropriately applies the mechanism by which lunar eclipses occur to explain the phases of the moon. Like Heather, the students who enter our science classrooms possess many incorrect notions that they use to explain scientific phenomena. The problem with these incorrect notions is that many are resistant to instruction. Students retain a considerable number of their erroneous beliefs following lessons in which lucid explanations are provided for the phenomena in question. Let us persist with Heather's story and see what happens:

> Heather receives formal instruction in her earth science class where explanations are provided on the causes of both the seasons and the phases of the moon. Two weeks following formal instruction, Heather is asked the same questions in another interview.
>
> Instruction has helped Heather overcome several of her misconceptions. For example, Heather now knows that it is not the shadow of the earth on the moon that causes the phases of the moon, but the relative position of the earth-moon-sun system as light rays from the sun strike the moon, reflect off it and hit the earth. Heather has also overcome her misconception about the curlicue path of the earth around the sun (she recalls that she had gotten that notion from a figure she saw in a science textbook). She now explains that the earth follows close to a circular path around the sun.
>
> Further, instruction has also changed Heather's view of the seasons being caused by the proximity of the earth to the sun since she now realizes that the earth is nearly the same distance from the sun during the course of a year. She explains by drawing a diagram that the seasons are caused by the tilt in the earth's axis, which causes direct and indirect light to fall on the northern and southern hemispheres of the earth (See Figure 1c).
>
> However, when asked to explain what she means by "direct" and "indirect" light, Heather resorts to her previous beliefs--she shows indirect light as being light that bounces off points in space, as light bouncing off a mirror, before hitting the earth. Even a strong hint from the interviewer where she is shown diagrams of what is meant by direct and indirect sunlight did not change Heather's mind. She incorporated the hint within her erroneous view by saying that the indirect light from the sun that caused winter in the northern hemisphere was light that bounced off some other point in the earth before reaching the northern hemisphere.

Heather was unable to overcome some of her misconceptions as a result of instruction. She interpreted the classroom lessons explaining direct and indirect light in view of her notions about the path taken by light from the sun (Figure 1b). Instruction, therefore, was only partially successful in helping Heather overcome some fundamental scientific misunderstandings. Heather is not unique. In fact, she is in good company. The same video shows interviews of Harvard graduates and Harvard faculty at commencement, all still wearing their caps and gowns, in which they display exactly the

same erroneous views about the causes of the seasons and the phases of the moon that Heather displayed prior to receiving formal instruction in ninth grade. The only difference between Heather and the Harvard graduates was that the Harvard graduates delivered their explanations with much more aplomb.

We might be inclined to interpret this scenario as evidence of the poor science teaching that takes place in American schools, but this interpretation would be not only far too simplistic, but also inaccurate. The science teacher who taught the ninth grade class was well-versed in earth science, was well-liked by her students, and would be judged a very good teacher by any evaluation team which observed her teaching methods. The truth is that scenarios like this are more the norm than the exception in American schools. Students from kindergarten to college who are taught by teachers who would be judged competent by any reasonable standard are emerging from science courses with a very poor understanding of both scientific concepts, and the nature of science in general. This situation mirrors the standing of American students in international science assessments; American students lag those from most industrialized nations in both science and mathematics achievement (IAEP, 1992).

It is against this backdrop that the recent educational reform movement in mathematics and science has emerged. The new reform movement is both a top-down and a grass-roots movement. At the top, the reform movement was being fueled by the then-President Bush and his Secretary of Education, along with the National Research Council and the National Governors Association. The document that is to serve as the strategy for the administration's educational reform, *America 2000*, is already in place, and one of its goals states that the U.S. will be number one in the world in science and mathematics achievement by the year 2000. Other reforms in science include the Scope, Sequence and Coordination project from the National Science Teachers Association, and Project 2061 from the American Association for the Advancement of Science (AAAS, 1989). The grass roots reform movement is far ahead in mathematics as compared with science. Mathematicians and mathematics educators, working through the National Council of Teachers of Mathematics, have constructed coherent plans for implementing change in both the mathematics curriculum (NCTM, 1989) and the teaching of mathematics (NCTM, 1991). Although no such documents exist in science, the National Academy of Sciences is beginning a process by which similar blueprints will be constructed by scientists and science educators.

What will it take for the new reform movement to have the desired impact on student achievement? There are some obvious ingredients that have to be present in order for any reform movement to have a measurable impact. These are adequate financial support, active involvement of scientists and educators, acceptance of the "final products" by science teachers, and educating teachers in the use of the final products whether they be curricular materials or instructional practices. It was the presence of these ingredients in the reform movements of the '50s and '60s that resulted in the scientific heyday of the '60s and '70s. Unfortunately, due largely to the erroneous assumption that the new materials would sustain themselves without continued revision and in-service teacher training, most of the excellent science materials that emerged from the previous reforms have all but disappeared from use in science classrooms today (Shymansky, Kyle, & Alport, 1983; Swartz, 1991).

There is one thing that sets the current reform movement apart from the post-Sputnik reforms. Today we have available a large (and growing) body of research findings on learning and problem solving in the sciences and mathematics. This body of research, generally termed "cognitive research," most of which has emerged over the last fifteen years, has important ramifications for learning and instruction. The focal concern of cognitive research is to understand the mental processes involved in the acquisition of knowledge and in the use of the knowledge to solve complex problems. A discussion of the nature of this body of research and its implications for learning and teaching science is the main goal of this chapter.

In this chapter I argue that, in addition to needing the ingredients mentioned above in a successful reform movement, two other factors should loom large in the development of new instructional materials in science and in the design of new instructional strategies. The first is cognitive research findings on teaching, learning, and problem solving. The need to have cognitive research findings guide curriculum development would seem obvious. If we were given the task of developing a faster computer, we would start by studying the newest, best available technology and then investigate how this new technology could be incorporated into making computers achieve faster computing speeds. We would not set about this task by resorting to simplistic approaches such as using thicker wires, or adding more of the same kinds of chips that are currently inside computers, or painting the computer casing in brighter, shinier colors. Yet, the latter is the approach of choice in developing commercial educational materials today. Textbook publishers and textbook writers largely ignore cognitive research findings and continue to clone new textbooks from best-selling existing textbooks or "improve" existing textbooks by adding color, changing the type size, or making similar cosmetic changes. Market considerations, more than learning considerations, drive the commercial publishing establishment.

The second factor that should influence curricular reform in science is the nature of science as it is practiced by scientists. If students are going to study a subject called "science" in school, then the science that they do should, in some way, reflect the views and practices of scientists. Although the science curricula that emerged from the post-Sputnik reforms reflected, albeit at a rudimentary level, science as it is practiced by scientists, the science curricula used in most American schools today do not. This, and the other issues raised above, are revisited in detail in the pages that follow.

So as not to create the wrong impression, I am not offering here "the solution" to the current underachievement of American students in science. Rather, I discuss issues of great importance in the formulation of a solution. Other issues that are equally important in formulating a solution--such as the pre-service and in-service education of teachers, the amount of time spent on science and mathematics by students both in and out of school, the role played by parents in their children's education, students' motivation to learn science and math, and the physical and mental safety of children in our school--are much too complex to treat in any single article, chapter, or book.

I begin by providing an overview of cognitive research findings on learning and problem solving in science and discuss the implications of this body of research for science instruction. I then examine how science is actually taught in our schools and argue that current instructional practices reflect neither our best understanding of learning and instruction, nor science as it is practiced by scientists. I then discuss possible reforms to bring about closer alignment between instructional practices and both current views of learning as well as scientists' views of science. I conclude with suggestions on the possible involvement of scientists, cognitive scientists, teachers, school administrators, parents, and

government officials in the current educational reform movement.

Research on Learning and Problem Solving in Science

In this section, three interrelated topics are discussed. First, I present a view of learning, called *constructivism*, which is widely held today because of its usefulness in accommodating a wide range of observations of human learning and problem solving behavior. I then discuss the role played by the knowledge that students already possess in learning scientific concepts and its relationship to constructivism. I conclude the section with a characterization of both unskilled and skilled problem solving behavior; the contrasts between skilled and unskilled problem solvers can be attributed in part to differences in the way knowledge is stored in memory and applied to solve problems.

Constructivism: Constructing (and Making Sense Out of) Our Knowledge

Perhaps the best way of appreciating the constructivist view of learning is to contrast it to its predecessor, the behaviorist view of learning. The behaviorist approach to teaching an individual some complex process is to break up the process into component parts, teach the individual each component, then teach the individual how to string together the various components until ultimately the desired behavior is obtained. Note the phrase "desired behavior." From the behaviorist perspective, the process is learned once the individual exhibits behavior that displays competence.

Conspicuously absent from the behaviorist approach are two things. The first is an interest in the cognitive mechanism used by the individual to learn the complex process. This would seem to be an important consideration since knowledge about learning might provide insights into how to shape instruction to make learning more efficient. Recent cognitive research, in fact, suggests that a complex process cannot be learned by decomposing and teaching individuals sub-processes without regard to the context within which the complex process will be performed. Knowing how the sub-processes interact within the context of performing the entire process is as important as knowing how to perform the individual sub-processes. In short, knowing the individual sub-processes does not "add up to" knowing the entire complex process (Resnick & Resnick, 1992). Also absent from the behaviorist approach is an interest in whether or not the process learned made sense to the individual. This also would seem to be an important consideration because if the process learned conflicts with knowledge already possessed by the individual, then the individual either will not be able to accommodate in memory the process learned in any meaningful sense or will construct parallel, conflicting knowledge structures.

To summarize, the focus of the behaviorist approach is the final manifestation of "competence" by the subject, not whether the knowledge learned made any sense to the subject, or whether the subject will be able to use the knowledge learned in novel contexts. Perhaps the behaviorist approach might be better described as training rather than educating.

Constructivism, which has its roots in the ideas of Jean Piaget, takes the point of view that individuals actively construct the knowledge they possess. This construction of knowledge is a life-long, effortful process requiring significant mental engagement by the learner. Further, the knowledge that we already possess affects our ability to learn new knowledge. If new knowledge that we are trying to learn conflicts with previously constructed knowledge, the new knowledge will not make sense to us and may be constructed in a way that is not useful for long-term recall or for application in a variety of situations (Anderson, 1987; Resnick, 1983, 1987; Schauble, 1990; Glasersfeld, 1989, 1992). In contrast to behaviorism, prior knowledge and sense-making are very conspicuous in the constructivist view of learning. (See Sidebar 1: Ernst von Glasersfeld on Constructivism.)

Constructivism has important ramifications for learning and instruction. In the constructivist view, the learner's mind is not a blank slate upon which new knowledge can be inscribed. Knowledge previously constructed by the learner will affect how he or she interprets the knowledge that the teacher is attempting to impart. In short, learners are not sponges ready to absorb the knowledge transmitted by the teacher in ready-to-use form. From the perspective of instruction, a constructivist teacher needs to probe the knowledge that learners have previously constructed and evaluate whether this knowledge conflicts with the knowledge being taught. If it does, the teacher must take care to guide learners in reconstructing knowledge; otherwise, there is no guarantee that learners will accommodate the new knowledge in a way that is compatible with current scientific thought. To ignore learners' pre-knowledge makes it highly probable that the message intended by the teacher will not be the message received by the student.

The discussion above would suggest that perhaps much of the confusion that students exhibit in learning scientific concepts might derive from conflicts between previously-constructed knowledge and the concepts they are trying to learn. Our discussion would also seem to suggest that simply making instructional presentations more lucid or persistent is not likely to alleviate students' confusion if it derives from such conflicts. The research findings on misconceptions described below confirm these conjectures.

The Initial State of the Learner: The Role Played by Preconceptions in Learning Scientific Concepts

By the time students enter our classrooms, they have been constructing knowledge for many years. The knowledge constructed by individuals is an attempt to organize experiences and observations so that they make sense and can be used to make predictions. For example, if a typical twelfth grader is asked to predict what will happen when a ball is thrown vertically up in the air, she would probably state that the ball will go up to some maximum height, turn around, and return to the place from which it was thrown. If she were asked to predict what would happen if the ball were to be thrown harder, she would probably say that it would go higher before turning around and returning. These kinds of correct predictions from our constructed knowledge let us function quite adequately on a day-to-day basis.

Along with the constructed knowledge about a ball thrown up in the air, students have also, during the course of their lives, constructed their own private understanding of concepts--such as speed, velocity, acceleration and force--concepts that have very specific meanings to scientists but that often have different meanings in daily parlance. This corpus of "private understanding" that students possess prior to receiving formal scientific instruction is usually fragmented, incomplete, and fraught with *preconceptions* , which are beliefs about the meaning and application of concepts within scientific settings

(DiSessa, 1988; Driver, 1990; Driver, Guesne, & Tiberghien, 1985; West & Pines, 1985). When preconceptions are in conflict with scientific concepts, which is a very common occurrence for students who have not received prior instruction in science, they are called *misconceptions* . (Other terms used in the literature for misconceptions are "naive theories" and "alternate conceptions.")

For example, if prior to taking physics the same twelfth grader were asked to discuss the thrown ball in terms of its acceleration, it is very likely that she would state that the ball would have a large acceleration just after it was released, that the acceleration would diminish as the ball ascends, becoming zero at the very top of the flight, and that the acceleration would again increase as the ball descends. This misconception, in which acceleration is treated as if it were equivalent to speed, is very common (Clement, 1981; Hestenes, Wells, & Swackhamer, 1992; Trowbridge & McDermott, 1980, 1981). If asked to discuss the thrown ball in terms of the forces acting on it, the student would likely state that the thrower gave the ball a large initial force which propels it along as it climbs. This "force of the hand," the student would claim, is possessed by the ball but diminishes as it ascends, becoming totally "used up" by the time the ball reaches the top of its flight. As the ball descends, it acquires increasing amounts of a new force, the gravitational force, which makes the ball pick up speed as it falls back to earth. This type of misconception, which is akin to the medieval theory of "impetus" [footnote 1], has been observed by various researchers (McCloskey, Caramazza, & Green, 1980; Clement, 1982; Halloun & Hestenes, 1985). Many other misconceptions have been uncovered in physics and are reviewed in various sources (Maloney, 1992; McDermott, 1984; Mestre & Touger, 1989; Novak, 1987; Pfundt & Duit, 1991).

Misconceptions are common across the sciences (Anderson & Roth, 1989; Anderson & Smith, 1987; Bishop & Anderson, 1990; Champagne, Klopfer, & Gunstone, 1982; Garnett & Treagust, 1992; Goldberg & McDermott, 1987; Hesse & Anderson, 1992; Thomson & Stewart, 1985). One study in biology investigated students' understanding of how plants made food (Wandersee, 1983). The study, conducted with students from grades 5, 8 and 11, as well as college sophomores, probed students' understanding of the role of soil and photosynthesis in plant growth, and of the primary source of food in green plants. Although students in the higher grades displayed more correct understanding, students from all grade levels displayed misconceptions. These included: the soil loses weight as plants grow in it, the soil is the plant's food, roots absorb soil, plants convert energy from the sun directly into matter, plants give off mainly carbon dioxide, the leaf's main function is to capture rain and water vapor in the air, plants get their food from the roots and store it in the leaves, chlorophyll is the plant's blood, chlorophyll is not available in the air in autumn and winter so the leaf cannot get food.

A study of students' understanding of earth science concepts (the same study from which the scenario at the beginning of this chapter evolved), revealed that many students believe that it is hot in summer and cold in winter because the sun is closer to the earth in summer than in winter (Sadler, 1987). Further, students' beliefs about why it was dark at night and light during the day included the moon blocks out the sun, the sun goes out at night, and the atmosphere blocks out the sun at night. Many of the students displaying these misconceptions had finished an earth science course in which the requisite knowledge was covered. The only difference between the erroneous answers of those who had taken the course and those who had not was that more technical jargon was used by those who had taken the course.

Research findings consistently show that misconceptions are deeply seated and likely to remain after instruction, or even to resurface some weeks after students have displayed some initial understanding immediately following instruction (Clement, 1982; Halloun & Hestenes, 1985). Heather's earth science teacher expressed surprise--even dismay--when viewing videotapes of Heather's understanding of the concepts taught in class (Pyramid Film & Video). This reaction is very common among science teachers in both high school and college once they fully realize what students' conceptual understanding is following science courses.

Because students have spent considerable time and energy constructing their naive theories, they have an emotional and intellectual attachment to them. Students cling to their erroneous beliefs tenaciously, often explaining away conflicts between scientific concepts and their naive theories by reinterpreting the lessons taught by teachers or by making inconsequential modifications to their theories. A clear example of this phenomenon comes from a study of children's understanding of the earth's shape (Vosniadou & Brewer, as reported in Chi, in press). Children who believe that the earth is square and are then told that it is round picture the earth as round like a pancake, not round like a sphere. If they are then told that it is round like a sphere, these children incorporate the new information about a spherical earth within their flat-earth view by picturing a pancake-like flat surface inside or on top of a sphere, with humans standing on top of the pancake.

What is deceptive is that students often display "understanding" in standardized science tests, in the tests constructed by teachers, or in text-embedded tests provided by textbook publishers, thereby giving teachers a false sense of their students' true understanding. Tests that probe for factual knowledge or that do not force students to apply the concepts covered in class in a wide range of situations will continue to show that students "understand" the material covered in class. What is clear is that without some catalyst, such as tests that probe for deep conceptual understanding (e.g., Hestenes & Wells, 1992; Hestenes et al., 1992) or classroom discussions where misconceptions are addressed, the mental engagement necessary for students to reconstruct their knowledge will remain absent.

Perhaps the most striking evidence that misconceptions are immune to traditional instruction is their prevalence among the general citizenry and even among experienced teachers. For example, in a recent study of misconceptions in astronomy and cosmology, 1,120 adults were asked to answer several multiple choice questions in a survey (Lightman, Miller, & Leadbeater, 1987). The findings revealed that 45% of respondents believed that the sun was not a star; that only 24% knew that the universe is expanding; that among those who stated they would be troubled if they found out that the universe was expanding, 92% were concerned that the expansion would present a danger to earth. Other studies reveal that experienced instructors exhibit misconceptions in basic introductory topics (Lochhead, 1980; Reif & Allen, in press). These data indicate that traditional instruction is not effective at imparting a deep understanding of scientific concepts.

Organization and Application of Knowledge in Solving Problems

Problem solving is ubiquitous in the sciences. Teaching students to become proficient problem solvers is also one of the most challenging tasks in science courses, especially in disciplines that are highly analytical, such as chemistry and

physics. To understand why it is so difficult for high school and college students to develop problem-solving skills in the sciences, we need only examine the ingredients necessary to be "proficient" at solving problems in a discipline such as physics: 1) An understanding of physics principles and concepts, 2) Ability to recognize which principles and concepts apply to problems varying widely in context, 3) Knowledge of procedures for applying the principles and concepts, 4) Knowledge of the mathematical form (equations) for the principles and concepts, and 5) Proficiency in the mathematics necessary to execute solutions. Clearly, being a proficient problem solver requires not only multiple proficiencies in these "higher-order" skills, but also a sophisticated mental management scheme for deciding which among several possible courses of action might prove fruitful, as well as how to piece together the many steps necessary for arriving at a solution once a course of action is selected.

To study such a complex process as problem solving, researchers have focused on investigating the performance of those who are proficient problem solvers, or experts, and those who are beginners but aspiring to become proficient problem solvers, or novices. The hope is that by comparing the performance of experts to that of novices, insights will emerge on how we might go about making more efficient the time-consuming transition from novice to expert. To date, the majority of expert-novice problem solving studies have been conducted in highly structured domains, such as chess (deGroot, 1965), electronic circuits (Egan & Schwartz, 1979), computer programming (Ehrlich & Soloway, 1984) and physics (Chi, Feltovich, & Glaser, 1981; Hardiman, Dufresne, & Mestre, 1989; Larkin, McDermott, Simon, & Simon, 1980).

Findings from expert-novice studies are often discussed within two categories: knowledge organization and knowledge use. Not surprisingly, research findings suggest that experts and novices organize their knowledge in memory rather differently. Currently it is believed that experts organize their knowledge into clusters of related knowledge referred to as "chunks," with the various pieces of knowledge in a chunk governed by an underlying principle or concept. The chunks, in turn, can be envisioned as comprising a richly interconnected hierarchical network, not unlike a pyramid, with the most fundamental principles and concepts occupying the higher levels of the hierarchy, followed by ancillary concepts, and with factual/mathematical information stored at the lowest levels. (Larkin, 1979; Glaser, 1992; Mestre, 1991; Mestre & Lochhead, 1990). Within such a model of knowledge, "knowing more" means having: 1) more conceptual chunks in memory, 2) more relations or features defining each chunk, 3) more interrelations among the chunks, and 4) effective methods for retrieving related chunks (Chi & Glaser, 1981).

Let me illustrate with an example of an experiment, the findings of which have contributed to the current perception of experts' knowledge organization. In this experiment (Egan & Schwartz, 1979), expert and novice electronic technicians were shown a complex circuit diagram for a very short time and then asked to reproduce as much of the diagram from memory as they could. The experts could reproduce accurately much of the circuit diagram following exposures of only a few seconds, whereas novices could not. The experts were capable of such remarkable recall by chunking several individual circuit elements (e.g., resistors and capacitors) that performed an underlying function in the circuit. For example, several circuit elements in a particular portion of the circuit diagram were chunked together as forming an amplifier, and thus by remembering the structure and function of a typical amplifier, the experts were able to recall the arrangement of the individual circuit components comprising the "amplifier chunk." To dispel the notion that the findings were simply the result of the experts having a better memory than the novices, both groups were shown circuit diagrams in which the circuit elements were arranged randomly, with no apparent function. Without the opportunity of chunking individual circuit components into functional units, the experts and the novices were equally poor at recalling the nonsense circuit diagram. The same findings have emerged from similar experiments in domains such as chess (deGroot, 1965) and computer programming (Ehrlich & Soloway, 1984).

There is also evidence that the hierarchical knowledge structure possessed by experts facilitates their ability to learn new related knowledge. For example, children who are experts on spiders are able to understand and recall the salient features of a passage on spiders after reading it, whereas children who are not knowledgeable about spiders cannot (Anderson & Shifrin, 1980). Similar findings have been observed in a study of individuals' comprehension of the game of baseball (Voss, Vesonder, & Spilich, 1980). Individuals possessing considerable knowledge about the game of baseball were able to recall the important features from a passage about a baseball game, whereas baseball-knowledge-deficient individuals recalled nonessential details about the passage. In short, the more one knows about a subject the easier it is to acquire additional knowledge about the subject. To use an analogy, having a highly organized filing system--with each filing cabinet labeled by a main theme, each drawer labeled with a sub-theme, and each folder within each drawer clearly denoting specific sub-sub-themes--makes it easy to store and retrieve large amounts of information. On the other hand, a filing system where large numbers of folders containing sub-sub-themes are strewn on top of a desk makes a highly inefficient information storage-retrieval system.

Major differences between experts and novices also emerge from investigations of how they use their knowledge to solve problems. One clear difference between the problem solving behavior of skilled and unskilled problem solvers lies in what problem attributes they cue on while deciding on a strategy for solving a problem. More specifically, shortly after reading a problem, skilled problem solvers cue on the underlying principle(s) or concept(s) that could be applied to solve it (Chi et al., 1981; Hardiman et al., 1989; Hinsley, Hayes, & Simon, 1977; Schoenfeld & Herrmann, 1982). In contrast, unskilled problem solvers cue on the objects and terminology used in problems as a way of deciding on a method of attack. For example, skilled problem solvers in physics decide that two problems would be solved with a similar strategy if the same principle (e.g., Newton's Second Law, Work-Energy Theorem) applies to both problems; in contrast, unskilled problem solvers base their decisions on whether the two problems share the same surface characteristics (e.g., both problems contain inclined planes, or pulleys and strings). Cuing on the surface characteristics of problems is not very useful since two problems that share the same objects and therefore "look" very similar may be solved by entirely different approaches, as Figure 2 demonstrates.

Expert-novice differences in knowledge use also emerge from observing the actions of individuals actively engaged in solving problems (see Figure 2). After deciding on the concept(s) that apply to a problem, skilled problem solvers next decide on a procedure by which the concept(s) can be applied, and then, in quantitative domains, apply the relevant formulas to generate answers. On the other hand, unskilled problem solvers resort to finding and manipulating equations that contain the quantities given in the problem until they isolate the quantity or variable being asked for (Chi, et al., 1981; Larkin, 1981, 1983; Mestre, 1991).

In summary, skilled problem solvers' tendency to conduct *qualitative analyses* of problems prior to executing the quantitative solution distinguishes them from unskilled problem solvers.

Our description of the tendency of novices to use a formulaic approach to solve problems should not be interpreted as a judgement of the uselessness of the approach. Clearly if it did not yield correct answers often, novices would have abandoned the approach in favor of more fruitful ones. This predisposition is more a necessity than a choice. Those who are starting to learn a subject do not yet have the appreciation or understanding of the subject's principles and concepts to be adept at knowing when and how to apply them. Equations, on the other hand, are easy to manipulate as long as one's algebraic skills are reasonably honed. Students are able to succeed with this approach because they can narrow down those equations that might be useful by knowing which portion of the textbook the problem came from and by matching the variables in the equations to the "givens" in the problem. It is only after considerable experience solving problems in this way that the unskilled problem solver begins to realize the lack of generality of the approach and begins to shift to concept-based problem-solving strategies.

Lack of Alignment Between Instructional Practices and Current Views of Learning

Given this brief overview of cognitive research on learning and problem solving, the obvious question is: "Do current teaching practices and commercially available curricula in science reflect our best understanding of how students learn and how skilled problem solvers solve problems?" I address this question from three perspectives. First, I discuss how science is taught in traditional curricula in grades 1-12. I then turn to commercially available curricula and evaluate whether or not they match current views of learning. Finally, since many argue that tests drive curricula, I also address this question by reviewing assessment practices in science. The evidence presented indicates that science instruction and curricula do not reflect current views of learning and problem solving.

Traditional Practices for Teaching Science in Grades 1-12

Transmittalist Instruction:

Traditional approaches to teaching science consist of presenting material through lectures while students sit quietly "learning" it. This approach, termed "didactic instruction" or "transmittalist instruction," assumes that students can absorb scientific knowledge while passively listening to instructors. A tacit assumption behind this method of instruction is that ability to understand the material being transmitted depends largely on the clarity of the presentation. If a student fails to understand, then making the presentation clearer or more insistent should make the material transparent for the student; often making a presentation clearer or more insistent translates to the teacher speaking slower and in a louder voice. As we have seen, this view is inconsistent with cognitive research findings. Transmittalist instruction is not optimal for the construction of knowledge by students and, unfortunately, is optimal for having students misinterpret the incoming information in terms of the knowledge that they have already constructed--knowledge that is often inconsistent with scientific concepts.

Although transmittalist instruction is used almost exclusively in college science courses as well as the majority of science classes in grades 1-12, it would be inaccurate to state that transmittalist instruction is the method of choice of teachers. Transmittalist instruction is part of a vicious cycle fed by two factors. First, we are inclined to teach the way we were taught, and it is very likely that we were taught with a transmittalist approach. Second, the information explosion in science places science teachers under pressure to cover an ever-increasing amount of material. Rather than focusing on teaching a few scientific concepts well enough so that students truly understand them and can apply them in a wide range of contexts, we focus on "covering" large bodies of "science facts." This leaves little time for identifying, reflecting and thinking about the few powerful scientific concepts that constitute the meat of a science course (Anderson, 1987; Arons, 1990; McDermott, 1990; Mestre & Lochhead, 1990; NRC, 1990; Smith & Neale, 1989). Learning science facts puts the students in a passive role, encourages memorization rather than the active construction of knowledge, and fails to connect the material covered in class with the student's previously constructed knowledge. Consequently, students lack a solid conceptual foundation after completing most science courses.

These statements should not be construed as stating that science instruction in American schools consists solely of transmitting facts about science, although research suggests that the weaker a teacher's background is in science, the more likely that this will be the case (Anderson & Roth, 1989). Teachers with strong backgrounds in science often model for students activities that are crucial in the practice of science, such as description, explanation, and prediction. Yet, students largely observe the teacher modeling these activities, rather than actively constructing the activities for themselves. Many excellent science teachers may present well-integrated knowledge to students, but students are not actively engaged in constructing such knowledge for themselves.

In defense of teachers, it also should be pointed out that much of the research that argues against a predominantly transmittalist instructional approach is fairly recent, and instructional applications of this research are only now beginning to trickle down to classroom teachers. It is also accurate to state that at the present time college instruction in the sciences does not reflect current views of learning. Before we have a right to expect that science teachers teach in ways consistent with constructivism, we need to demand the same consistency in the type of science instruction that these teachers receive in college.

Ineffective Teaching of Conceptual Knowledge

The research findings reviewed above suggest that, in order to teach in a way that reflects constructivism and that incorporates the implications of cognitive research on problem solving and conceptual development, teachers need to possess a mental framework consistent with these views that guides their instruction. The mental framework that teachers possess, however, is one based on the transmittalist model that was used in their own schooling. That is, teachers' cognition of instruction is incompatible with current views of learning and instruction. Classroom observations at all levels indicate that teachers seldom take into account the conceptual knowledge previously constructed by students (Arons, 1990;

Anderson & Roth, 1989; Anderson & Smith, 1987; Smith & Neale, 1989; McDermott, 1990). During the course of instruction, students' ideas, predictions, and explanations of science phenomena are not probed to monitor whether the concepts being taught are in conflict with students' prior notions.

Science instruction that is specifically structured to encourage conceptual change in students requires that teachers be well versed in three important areas (Anderson & Smith, 1987). First, teachers must possess a command of the content of science at a level sufficient to distill the big ideas and methodology from the less useful facts and rote procedures. Without sufficient content knowledge, teachers will be unable to recognize when students' conceptual knowledge is incomplete or inconsistent with scientific concepts. Second, teachers need to have a working knowledge of constructivism and of the cognitive research literature as it pertains to learning science. Third, teachers need to have a working knowledge of constructivist instructional strategies for promoting and monitoring students' conceptual understanding.

Teachers' knowledge in these three areas is relatively weak across all grade levels. The weaknesses are greatest at the elementary level. Lack of science content knowledge (i.e., knowledge of principles, concepts, definitions, problem solving procedures, experimental and data analysis techniques) is most prevalent among elementary school teachers (Schmidt & Buchmann, 1983) largely due to the minimal science requirements imposed by colleges and universities on those wishing to become certified in elementary education. Lack of science content knowledge makes it difficult, if not impossible, for teachers to identify misconceptions in students. In fact, primary teachers often exhibit conceptual flaws similar to children's misconceptions (Smith & Neale, 1989). Because many elementary teachers feel unprepared in science (Weiss, this volume), they often spend little time teaching it and are especially loath to teach physics topics, which they know least about (Smith & Neale, 1989). The science taught in elementary school is usually right out of textbooks (Weiss, this volume), and as I argue below, elementary textbooks offer little more than lessons in scientific vocabulary. Further, teachers at this level believe that they need to know the answers to questions children might ask, and that without an encyclopedic knowledge of science they will be unable to teach it. The view that science is a process of inquiry that allows us to ask answerable questions, to design methods for answering the questions, and to organize our answers under a few powerful principles is foreign to most teachers at this level.

At the middle school and high school levels, relatively few science teachers meet the course-completion standards recommended by the National Science Teachers Association (NSTA); only 25% of middle school science teachers met NSTA's standards; only 29%, 31%, and 12%, of high school biology, chemistry, and physics teachers, respectively, met NSTA's standards (Weiss, this volume). A considerable number of teachers teach science subjects in which they received no formal education (Anderson & Smith, 1987; Neuschatz & Covalt, 1988). In addition, high school science instruction is severely lacking in terms of teachers' knowledge of students' thinking and of constructivist epistemology (Berg & Brouwer, 1991); transmittalist-style instruction predominates in high school science instruction (Weiss, this volume).

Ineffective Teaching of Problem Solving

Problem solving instruction in our schools generally does not emphasize techniques used by skillful problem solvers. In high school physical science courses the emphasis is usually on problem-specific procedures and mathematical manipulations to help students get answers, rather than the application of powerful ideas and generalizable procedures that could be applied across a wide range of contexts (Mestre, 1991). The lack of emphasis on qualitative reasoning and on integrating conceptual knowledge within problem solving instruction encourages rote memorization of procedures and formulaic approaches that do little to foster conceptual understanding. The problems that students solve often illustrate a single path to a single answer; the notion that a problem may have multiple solutions or multiple paths to a solution is not stressed.

Although many teachers discuss the role of concepts in solving problems, students often focus on the quantitative aspects of the solution rather than on the conceptual aspects. For example, typical approaches for teaching problem solving in physics consist of cycling through a three-step process: concepts are presented, then how they are used to solve problems is illustrated, and finally students are given lots of problems to solve on their own. Although instructors are usually careful to mention what principles and concepts are being applied when they work out problems in front of a class, they often only write down the equations that result from these applications. Consequently, students perceive the quantitative aspects of the solution as being primary and the conceptual aspects as being abstractions that bear little relevance to generating answers. With this perception, having students solve lots of problems on their own may only reinforce formulaic approaches. Students who undergo such a regimen often achieve good grades on exams made up of standard problems, but they fail miserably when asked questions that probe for understanding of the concepts underlying the problems' solutions (Anderson, 1987; Clement, 1982; Hestenes & Wells, 1992; Hestenes, et al., 1992; McDermott, 1991)

At the elementary level, the solutions to the "problems" that students are given usually require only single words or phrases; in that sense, elementary students do not solve problems but rather answer questions (Anderson & Roth, 1989; Goldberg & Wagreich, 1990). Students typically are not given open-ended problems that require them to break problems into smaller sub-problems, to devise mathematical or experimental methods for answering the sub-problems, or to summarize the knowledge learned from solving problems in a form that makes it conducive to applying it in novel contexts.

Inadequacies in the Teaching of Laboratory and Experimental Skills

Experimentation is at the heart of scientific inquiry. This is perhaps why laboratory work and "hands-on" activities are so prevalent in teaching science. Yet, a critical analysis of the types of lab activities that students engage in indicates that they do not reflect what scientists actually do in the laboratory. What do scientists do when they practice the art of experimentation? Often planning an experiment begins with a question or series of questions that are of interest to the scientist, that have not been answered previously, and that he or she thinks can be answered within the laboratory. The scientist then has to decide how to go about planning the experiment; equipment may have to be designed, built, or bought; experimental procedures need to be planned to isolate the variable(s) to be studied; and data analysis techniques need to be planned to extract the relevant information from the experimental output. Findings from experiments are then analyzed and compared against findings from other related experiments and evaluated in light of existing theories. Perhaps the findings can be used to extend or refute existing theories. The entire process is open-ended and may be filled with technical and procedural obstacles. It is safe to say that experimentation in a research laboratory does not come with a detailed list of

procedural steps which, if followed, will result in the desired outcomes. Clearly it would be unrealistic to demand that experimental work in science classes has all the attributes of experimentation in a research laboratory. We could demand that it reflect some of the activities that scientists actually engage in, however.

Unfortunately, laboratory experiments in science classes are fairly cut-and-dried activities usually designed to verify known phenomena, not to make observations and formulate principles (Goldberg & Wagreich, 1990; McDermott, 1990; Mestre & Lochhead, 1990). The "cookbook" nature of experiments leaves students with the impression that scientists follow predetermined procedures to arrive at their discoveries (NRC, 1990). Perhaps this view is fed by the assumption by many scientists and educators that laboratory work should support the lecture portion of the course. Research studies suggest, however, that laboratory work designed to reinforce the concepts covered in lecture do little over and beyond what students learn with a lecture presentation alone (Dubravcik, 1979; Kruglak, 1952, 1953; Robinson, 1979).

Of the three important functions that experimental work could serve in science classes--namely teaching experimental skills; teaching data handling, analysis and interpretation skills; and teaching the process of scientific inquiry--only the first two are feasible within the structured experiments that students perform. Teaching experimental skills and data analysis techniques are very important aspects of science instruction, and these skills can be rather difficult to teach. Studies indicate that fifth- and sixth-grade children do not record plans or previous experiments in logbooks, preferring to rely on memory to recall experiments that they had performed over an eight-week period (Schauble, 1990). Children also display biases and strategic weaknesses in experimentation, such as unsystematic searches, failure to control variables, distorting evidence to preserve favored theories, and logical errors in interpreting patterns of data (Schauble, Klopfer, & Raghavan, 1991). By the time they get to college, many students still have not acquired these skills (Arons, 1990). On the positive side, studies have shown that students who perform hands-on laboratory activities are better than those who do not on skills such as using lab apparatus, making measurements and observations, analyzing data, and following safety procedures (Kruglak, 1952; Beasly, 1985; McDermott, Piternick, & Rosenquist, 1980a, 1980b, 1980c).

The one function that cookbook labs cannot perform is to teach scientific inquiry. Spelling out the purpose of the lab, the apparatus to be used, the steps to be carried out, a procedure for analyzing the data, and the expected findings encourages mental passivity in students (Tinnesand & Chan, 1987). With cookbook labs, students are not asked to consider why the hypotheses or questions under consideration are meaningful, why or how the particular apparatus and procedural steps were selected, and how the experimental findings can be used to construct, support, or disprove scientific hypotheses.

Is the solution to teaching scientific inquiry to turn cookbook labs into open-ended labs--that is, labs where students are given a general problem and general guidelines and equipment to use in designing and executing an experiment? Although open-ended labs are a more accurate reflection of what scientists actually do in the laboratory, there are major obstacles with implementing them in school. Open-ended labs are much more time-consuming than cookbook labs, and thus they are hard to schedule in the typical one or two hour weekly lab periods that students are allotted for laboratory work. Students do a lot more floundering in open-ended labs, and thus classroom management becomes a major problem. Nevertheless, a compromise between cookbook labs and open-ended labs, termed "structured inquiry," is possible and is discussed in a subsequent section.

Commercially Available Curricula in Grades 1-12

Textbooks set the tone for science instruction in schools since many teachers use them as blueprints for instruction (Weiss, 1987, this volume). Unfortunately, commercially available textbooks do little to promote constructivist epistemology, conceptual change, or skillful problem solving. I discuss below some of the problems with commercially available curricula for elementary, middle, and high school students.

Recent evaluations of commercially available elementary science textbooks indicate that they are fraught with problems (Anderson, 1987; Goldberg & Wagreich, 1990; Mestre, 1991; NRC, 1990). The first thing that is apparent is that elementary school textbook series are largely clones of one another. Many of the same topics are covered each year, not in an attempt to increase students' understanding of the concepts involved, but rather in an attempt to add more details, facts and definitions with increasing grade level. New scientific words are highlighted in boldface type to emphasize their "importance." The "main ideas" listed in the back of each chapter are mostly definitions and facts, not ideas. Although rare, some texts do contain useful explanations of concepts, but these are not highlighted nor are students challenged to think about the underlying meaning of these concepts. In attempts to simplify the science, errors are often committed; for example, in the light unit of a third grade science text we find the statement: "Light cannot go around objects" (Cohen, Cooney, Hawthorne, McCormack, Pasachoff, Pasachoff, Rhines, & Slesnick, 1989, p. 152). Light, in fact, can diffract, or bend, around objects.

In addition to echoing the view that the material covered in elementary science textbooks is a random collection of unrelated topics and facts, other critics point out additional shortcomings (Brown & Campione, 1990). For example, the narrative style used to make the presentations more captivating makes it difficult for the student to distinguish fact from fantasy. Further, presentations assume a developmental progression, such as categorizing shapes and colors in first grade, animals by habitat in fourth grade, and vertebrates and invertebrates in eighth grade. However, no apparent rationale is provided for how each activity prepares students for the next, more "advanced," activity or how this progression will help students form a coherent view of science. Finally, in the problems and exercises provided there is almost a total emphasis on recalling facts (e.g., "what happens" types of questions) rather than on explaining phenomena (e.g., "why does it happen" types of questions). Without the mental engagement necessary for conceptual change, students often distort what they read because of strongly held prior beliefs that conflict with textbook passages (Roth, as described in Anderson, 1987)

For students who are taught science from such textbooks, "understanding" means that they are prepared to answer recall questions on the material since this is the only type of understanding they are asked to display (Anderson & Roth, 1989). Thus the learning that takes place is learning facts about science, not learning science--rarely are students asked to apply knowledge in performing activities in which scientists engage, such as describing, explaining, predicting, and controlling the world around them.

From the publishers' perspective, writing elementary science textbooks that emphasize factual knowledge is an excellent idea from a marketing perspective. A curriculum that portrays science as a body of facts is a curriculum that any teacher can teach. Possessing sufficient knowledge of science content, of students' thinking, and of instructional strategies consistent with constructivism become unimportant within a fact-based science curriculum. (See Sidebar 2: Commentary on Biology Textbooks.)

At the middle school level, except for cosmetic changes, the textbooks remain similar to those at the elementary level (Harmon & Mungal, 1992a, 1992b; NRC, 1990, Swartz, 1991). The "factual flavor" is very much alive at this level as well. For example, at the very beginning of a popular middle school science textbook, we find the following definition of science: "Science is the knowledge of all the facts that are known about the world and the methods or processes used to learn or explain these facts." (Feather, Ortleb, Blume, Aubrecht, & Barefoot, 1990, p. 6) The remainder of the book is long on the facts of science and short on the "methods or processes used to learn or explain" the facts. The laboratory activities that accompany middle school curricula do not promote a spirit of inquiry, but rather are designed to verify known phenomena. Such lab activities promote an authoritarian view of science as a body of factual knowledge that is revealed only if the scientific method is followed (Pizzini, Shepardson & Abell, 1991).

High school biology textbooks suffer from including excessive amounts of science factual information. For example, a recent review of a high school biology textbook averaged 109 new terms per chapter in its 30 chapters (Sutman, 1992). Another common complaint from scientists is that biology textbooks are fraught with content errors (NRC, 1990). The same biology textbook mentioned above averaged one error per page. The emphasis on (often inaccurate) factual information in textbooks leaves little opportunity for inquiry activities and for extracting and making sense of the major concepts underlying biology.

In high school physical science, where problem solving begins to play an important role, popular texts illustrate problem solving as algebraic manipulation by illustrating worked-out examples in which so-called "basic equations" are found and manipulated to yield answers (see Figure 3). Little or no attempt is made to discuss the application of concepts or ideas that would alert students to the importance of conceptual knowledge in solving problems. Rather than selecting textbooks on the basis of accuracy of presentation and sound pedagogic strategies, high school teachers often select texts in terms of how attractive they look (McDermott, 1990).

Very few science curricula reflect research findings on learning and problem solving. Many of the existing exemplars are often labeled "experimental," however, or are still under development and not commercially available. Some new, innovative physical science curricula for grades 1-12 are listed in a recent article (Salinger, 1991).

Traditional Student Assessment Practices

An examination of traditional student assessment practices indicates that they do not support a curriculum the focus of which is the teaching of conceptual knowledge and problem solving skills. For the moment, let us consider the types of standardized achievement tests used for purposes of public accountability, a major use of student assessment today. An example of this might consist of evaluating a school system's performance by assessing students' knowledge in numerous subjects. Three problems plague standardized achievement tests: 1) The format of the tests; 2) The behaviorist assumptions underlying them; and 3) The effect these tests have on the curriculum.

The format of the vast majority of standardized achievement tests administered to the students in a school or district is "multiple choice." Recent studies that have scrutinized the questions asked in multiple choice achievement tests in mathematics and science indicate that they focus on the recall of routine factual knowledge, not on problem solving (Harmon & Mungal, 1992a, 1992b; Murnane & Raizen, 1988; Resnick & Resnick, 1992). Further, the multiple choice format conveys the impression that the answer is already known, and so imaginative methods for obtaining the answer are not expected. Finally, selecting the correct answer from an array of choices is not an accurate depiction of what people do when they solve problems in the real world.

Multiple choice achievement tests tacitly enact a behaviorist perspective by assuming that complex knowledge can be tested by decomposing and decontextualizing it into an "archipelago" of questions, the sum of which is supposed to equal the "continent" of students' knowledge. As pointed out above, however, cognitive research indicates that knowing the separate parts is not equivalent to knowing the whole.

Finally, accountability tests tend to drive the curriculum (Lomax, West, Viator, & Madaus, 1992; Resnick & Resnick, 1992). Teachers feel under considerable pressure to have their students "measure up" in achievement tests. A poor showing in an achievement test by a particular teacher's class, a particular school, or an entire district may have far-reaching consequences, such as affecting teacher salaries, school budgets, or academic ratings for the school or district. Therefore, an inordinate amount of time is spent by teachers "teaching to the tests" in order to improve students' performance. The result is that students are taught a collection of definitions and bits of isolated information that will allow them to "get the right answer" on the tests, rather than a cohesive corpus of knowledge and analytical skills for using that knowledge to solve novel problems.

In summary, current student assessment practices, as implemented in standardized achievement tests used by schools for purposes of public accountability, only guarantee that what is taught closely reflects what is assessed. In other words, what is not assessed is not likely to be taught (Resnick & Resnick, 1992). Perhaps the most efficient method for reforming science education is to design assessment instruments that require a demonstration of conceptual understanding and genuine problem-solving skills.

Factors Necessary to Bring About Alignment Between Instructional Practices and Current Views of Learning

In the section above I argued that current instructional practices are poorly aligned with our best understanding of learning and instruction based on cognitive research findings. In this section I discuss the types of changes necessary to bring

about alignment. I break this discussion into the types of reforms needed in the teaching of: 1) conceptual knowledge, 2) problem solving, and 3) scientific inquiry. I also address the types of bold reforms necessary to bring about desirable changes in commercially available curricula and in assessment practices.

Strategic Instruction: Teaching Strategies Based on Cognitive Research Findings

Reforming the Teaching of Scientific Concepts

As reviewed above, current views of learning hold that effective instruction must take into account the knowledge that students have already constructed. Teaching that simply transmits knowledge to students is not optimal since the scientific knowledge being transmitted will likely conflict with knowledge already possessed by the student. Under transmittalist instruction, students often interpret the incoming knowledge in terms of previously constructed erroneous knowledge. Hence the knowledge that the teacher attempted to impart may not be equivalent to the knowledge that the student acquired. What are important ingredients for teachers to incorporate into their "cognition of instruction" to optimize students' learning of scientific concepts?

In shaping instructional approaches for imparting scientific concepts teachers need to keep in mind the conditions under which students overcome misconceptions. Posner, Strike, Hewson and Gerzog (1982) argue that four conditions need to be present in order for students to undergo a conceptual change: 1) Students must become dissatisfied with their existing conception; if students believe that their (erroneous) conception accurately describes scientific phenomena, they would not see a compelling need to change it; 2) Students must possess some minimum understanding of the scientific concept; without some initial minimal understanding, students cannot begin to appreciate its meaning; 3) Students must view the scientific concept as plausible; if the scientific concept is incompatible with other concepts residing in the students' memory, it is not likely that serious consideration will be given to it; and 4) Students must view the scientific concept as useful for interpreting or predicting various phenomena.

Although there is no single, optimal instructional approach for bringing about conceptual change, the four conditions above suggest the presence of some essential ingredients in crafting instruction designed to encourage conceptual development (Anderson, 1987; Asoko, Driver, & Scott, 1992; Duckworth, Easley, Hawkins, & Henriques, 1990; Mestre & Lochhead, 1990; Neale, Smith & Johnson, 1990; Smith & Neale, 1989). First, instruction should take into account students' beliefs; we should listen to students ideas about science and not just transmit our ideas about science to students. Only by probing for understanding will teachers be able to determine when students possess misconceptions that are in conflict with the scientific concepts targeted for instruction. In addition, teachers need to possess considerable knowledge of science content in order to be able to determine whether the conceptions held by students are misconceptions. Further, when a misconception is identified, a teacher needs to be able to induce dissatisfaction in students in order to initiate the process of conceptual change. To create dissatisfaction requires that the teacher be able to challenge students by providing discrepant events that illustrate inconsistencies between their belief and scientific phenomena. When discrepant events are presented or experienced, students need to debate and discuss the scientific concept in view both of their beliefs and the discrepant events. The teacher then needs to help students appreciate the value of the scientific conception in terms of its consistency with other scientific concepts and of interpreting other phenomena and making predictions. Finally, the teacher needs to guide students in reconstructing their knowledge. Figure 4 provides an example of an approach for helping students overcome the "force of the hand" misconception discussed above.

The major ingredients in conceptual-change teaching--namely probing for and identifying misconceptions, providing discrepant events, and guiding students in reconstructing knowledge--place heavy cognitive demands on teachers. The teacher must perform these tasks "on the run," often while attempting to maintain a delicate balance between argumentation and order within the classroom. As stated above, conceptual-change instruction requires that teachers possess three types of knowledge: science content; concepts already possessed by students prior to science instruction; and instructional strategies to facilitate and monitor conceptual change.

Helping teachers form a new vision of learning and instruction that incorporates these three types of knowledge may seem an impossible task given traditional teacher-education practices. Reshaping pre-service and in-service teacher education programs may be difficult but certainly not impossible. What is clear is that some significant changes in teacher education programs are necessary and that the changes must meet needs that differ across grade levels. The science content knowledge of elementary and middle school teachers has to be upgraded, but this does not mean that in-service and pre-service teachers need to take an inordinate number of science courses. We need to be selective and pare down the number of science topics that teachers study and concentrate on giving these teachers a thorough understanding of a few topics, rather than a superficial understanding of most of the scientific knowledge in this and the previous century. Further, teachers not only need to experience science instruction in college from an inquiry perspective, but also need to become well versed in teaching science in this fashion. Possessing a thorough conceptual understanding of selected science topics and having a solid grounding in inquiry instruction will allow elementary and middle school teachers to teach a few scientific concepts well and to provide students with a better perspective of what "doing science" really is. The view that "less is more" in teaching science content is one being advocated at all levels of science instruction (Arons, 1990; McDermott, 1990; Mestre & Lochhead, 1990; NRC, 1990; Sutman, 1992).

The inadequacy of teachers' knowledge of students' beliefs about science and about scientific concepts is a persistent problem across all grade levels. Although there is a large, ever-increasing body of research on students' preconceptions and misconceptions, many pre-service as well as in-service teacher education programs either ignore this pertinent body of knowledge or simply give it lip-service without adequately attending to it. It may seem a herculean task to instruct teachers in the countless misconceptions that students are likely to possess. Research indicates, however, that although misconceptions are prevalent, the number of distinct misconceptions in any given topic is quite small (Mestre & Lochhead, 1990). Thus, the task of providing teachers with a perspective of students' beliefs as they study science content is quite manageable.

Perhaps teaching teachers instructional strategies that foster conceptual change is the most difficult of the tasks, largely because most of the cognitive research effort to date has focused on studying learning rather than instruction. Nevertheless, some promising instructional strategies that reflect both the constructivist view of learning and the need to

consider students' prior knowledge are beginning to emerge (Anderson & Smith, 1987; Asoko et al., 1992; Brown & Campione, 1990; Minstrell, 1989; Clement, 1991; Smith & Neale, 1989; Van Heuvelen, 1991). These instructional strategies have many features in common, the most obvious one being that students are actively engaged in constructing scientific knowledge. The teacher takes on the role of coach rather than transmitter of knowledge. Classroom discussions of concepts are common, either within collaborative groups of three or four students, or with the entire class with the teacher as moderator. These discussions focus on scientific concepts, with students' prior notions being probed by the teacher and by other students. This approach should not be confused with discovery learning, where students are urged to discover scientific concepts on their own. Scientific facts and concepts are transmitted to students in conceptual-change instruction, but the emphasis is active engagement by students in constructing accurate mental representations of scientific concepts. Figure 5 contains an example of what a discussion of the concept of acceleration might look like in a high school physics classroom.

Two caveats should be mentioned. Some may get the impression from the foregoing discussion that conceptual-change instruction is tantamount to a crusade of finding and eradicating students' misconceptions. This is not the case. The constructivist view takes cognizance of the fact that students' conceptual knowledge evolves in time, and many misconceptions will disappear naturally as students gain expertise (Driver, 1990). The foregoing discussion should create the impression that ignoring how students interpret and construct the concepts that are taught in science class leads to inefficient learning.

The second caveat is that the three "knowledges" needed by teachers for conceptual-change instruction are inextricably related and should be taught as a package. Teaching teachers science content alone means that they will be able to understand scientific concepts and model the process of doing science for students, but that they may be incapable of monitoring students' conceptual understanding or helping students construct scientific concepts. Conversely, it has been observed that teachers who are weak in science can be taught instructional strategies both for eliciting students' misconceptions and encouraging discussion and debate. Without an adequate knowledge of science content, however, they were unable to recognize students' misconceptions or provide discrepant events--in short, they were unable to induce conceptual change in students (Smith & Neale, 1989).

What is clear is that making the transition to conceptual-change instruction in an educational establishment with a long-standing tradition of transmittalist instruction will not be easy. As in our previous discussions of the nature of expertise, it will take time for in-service teachers to reconstruct their "cognition of instruction" and become experts in the ways of conceptual-change instruction. Although in-service teachers may be experts in conventional teaching strategies, they will have to begin afresh as novices in conceptual-change teaching strategies. The time required to construct the necessary knowledge to become an expert in conceptual-change instruction means that progress will be slow, with no short-term solutions available.

Reforming Problem-Solving Instruction

Close scrutiny of our previous review of problem-solving research indicates that two ingredients play a major role in skillful problem solving: 1) a substantial, richly cross-referenced, hierarchically organized knowledge base; and 2) qualitative reasoning based on conceptual knowledge. There is research evidence that we can shape our instruction to help students develop in these two areas so that they will display more skillful problem-solving behavior.

Shaping instruction to help students organize their knowledge hierarchically must begin by curbing our tendency to present knowledge in our classes and textbooks in a linear fashion. Students must be provided with a perspective to help them realize that concepts are useful due to their applicability in a wide range of contexts. As new knowledge is presented, students should be assisted in linking this new knowledge to previously learned knowledge and in building a hierarchical structure where ancillary concepts are placed below, and linked to, major concepts. The relationships among major concepts, and between a major concept and its entourage of ancillary concepts, need to be made explicit during the course of instruction. Attending to how we should present and relate content knowledge, as well as to how students organize this knowledge, is as important as the content knowledge itself (Reif, 1986).

Figure 6 depicts a way of helping students structure their knowledge. This figure shows two biology teachers' organization of biological knowledge from the "reproduction" portion of a typical introductory biology course. Students should be asked to construct, add to, and refine such tree-like structures at different times during instruction in the science courses they take [footnote 1] . Another approach that has shown promise in physical science is to present knowledge hierarchically, with calculational details subordinated to main principles that are first outlined to provide overview (Eylon & Reif, 1984). When presented in this fashion, students were better able to recall the knowledge and use it in problem-solving contexts.

Several tasks can be used to encourage qualitative reasoning. For example, problem categorization tasks (Chi et al., 1981; Hardiman et al., 1989) are useful for helping students identify and discuss the underlying concept(s) that can be applied to solve problems. The task that students would be asked to perform is not to solve the problems but to read them carefully and discuss which concepts might be fruitful to apply in constructing a solution. One of the virtues of these types of tasks is that teachers can construct pairs of problems that share the same surface characteristics but are solved by applying different concepts (e.g., see Figure 2). Conversely, teachers can construct pairs of problems that, on the surface, look quite different but are solved by applying the same concept. Having students work with these problem pairs would serve the dual role of alerting them to the usefulness of concepts and dissuading them from the temptation to cue on surface attributes in designing solution strategies.

Other approaches for encouraging qualitative reasoning focus on having students construct qualitative strategies for solving problems prior to actually generating a quantitative solution. For example, in two different studies (Dufresne, Gerace, Leonard, & Mestre, 1991; Heller & Reif, 1984) physics novices were asked to generate qualitative analyses of problems in which they described the principles, concepts and procedures that could be applied to solve the problems. As a result, these novices displayed increased expert-like problem-solving behavior when compared with novices who followed traditional methods for solving problems. Similar findings were obtained in a series of studies (Mestre, Dufresne, Gerace, Hardiman & Touger, 1992; Dufresne, Gerace, Hardiman, & Mestre, in press) in which students constructed hierarchical qualitative strategies using a menu-driven, computer-based environment that mimicked the

qualitative analyses used by experts.

Open-ended problems can also serve as a catalyst for encouraging the use and integration of conceptual knowledge. For example, in "design-under-constraint" problems, students are provided with a real-world design problem and some broad constraints that the solution must satisfy. Examples might be: "For $5 design a meal for four kids that is nutritionally correct and that kids will eat"; or "design a disposable container to keep a baked potato warm--the potato should not lose more than 10 deg.C in half and hour" (Salinger, 1991). These types of problems are well-received by elementary school teachers because they have multiple "right" answers. Other types of open-ended problems can be designed that may have a single answer but multiple paths to it. Examples from biology and chemistry might include determining the optimal salinity of water to be used to ship brine shrimp to a friend, and determining which of two liquids is the regular soda pop and which is the diet version (Baron, 1991).

Additional instructional approaches are beginning to emerge that describe methods for helping students develop qualitative reasoning based on conceptual knowledge. Some provide theoretical underpinnings as well as practical suggestions (Arons, 1990), others provide detailed suggestions that incorporate hands-on experiences (Laws, 1991; Rosenquist & McDermott, 1987; Thornton & Sokoloff, 1990), while still others even illustrate methods for turning large college lecture physics courses into interactive environments where students actively discuss how concepts are applied to solve problems (Van Heuvelen, 1991). Some approaches even exploit the emphasis given to language arts at the elementary grades by using collaborative learning techniques within reading lessons to teach science (Brown & Campione, 1990).

Reforming the Teaching of Laboratory and Experimental Skills

I argued above that although cookbook labs may be useful for teaching students some experimental skills and data analysis techniques, they are not adequate for teaching scientific inquiry. At the opposite extreme, open-ended labs, or unstructured "hands-on" activities, are also not likely to promote scientific inquiry for a number of reasons. Open-ended lab activities are very time-consuming, with students going in multiple paths many of which prove to be dead-ends. Open-ended labs also present classroom management problems for teachers. And, without direction, students are unlikely to control variables, synthesize data and form or test hypotheses. I now describe one approach for teaching both experimental skills and scientific inquiry, called "structured inquiry," that lies somewhere between these two extremes (Mestre & Lochhead, 1990).

The idea behind the structured inquiry approach is to provide a structure within which to carry out experimental work, but one that allows students the freedom to explore and learn on their own. Rather than providing all the details of an experiment, as in cookbook labs, the structured inquiry approach provides students with both a designated topic that will be the focus of the experiments and the equipment available to conduct the experiments. The teacher's role is to serve as coach, mediator, and facilitator.

The structured inquiry approach cycles through three stages. The first consists of a classroom discussion of experimental design. After the topic for investigation and available equipment are indicated, students would propose questions and pose hypotheses and discuss possible experiments and experimental procedures that could be carried out with the available equipment to explore the proposed questions and hypotheses. Since posing meaningful questions will likely be difficult for students, the teacher must be ready to provide the necessary assistance so that students do not spend an inordinate amount of time floundering. This discussion stage is likely to generate several experimental questions and procedures, all of which cannot be investigated by an individual student. To ensure exploration of all relevant questions, the teacher can then divide the class into collaborative working groups, each having the responsibility of exploring a question or related set of questions.

In the second phase, the students carry out the experimental work. The teacher needs to circulate and provide guidance and instruction to the various groups on useful techniques for observation, measurement, and analysis. After the experimentation is completed, the groups perform a preliminary analysis of their data and draw preliminary conclusions.

In the third phase, the classroom reconvenes for another discussion of the experimental findings. Now the various groups can pool their findings and work on answering the questions or hypotheses posed in phase one. This discussion of the experimental findings might result in the posing of additional questions or hypotheses that need to be explored through experimentation, and hence the cycle might begin again. Structured inquiry proposes a compromise between activities that are doable in the classroom and activities that reflect the experimentation that scientists actually practice in their laboratories.

There are some notable examples of science curricula that model the types of activities described above. The Teaching Integrated Math and Science curriculum (Goldberg & Wagreich, 1990) is aimed at the elementary grades and employs laboratory activities that are of interest to children and that lend themselves to an inquiry approach. In each activity, students design experiments to explore the relationship between pairs of physical variables (e.g., how the height to which a ball bounces depends on the height from which it was dropped). At the middle school level, the Cheche Konnen project (Warren, Rosebury, & Conant, 1990) focused on studies of chemistry, biology, and ecology to investigate problems that students believed existed in their school's water supply. The students in this project, who were Haitians with limited English proficiency, designed their own experiments to test a hypothesis they had, namely that water from a particular water fountain in the school tasted better than water from other fountains. Their inquiry began with an in-class experiment consisting of a "blind" taste test of water taken from different fountains in the school. When the data from this experiment did not support their hypothesis, students did not believe the findings. They then decided to carry out another experiment using students drawn from the entire school. Thus, another "blind" taste test was set up in the school cafeteria during lunch one day, and additional data were collected. The data from this experiment also refuted the students' initial hypothesis--water from their favorite fountain, in fact, tasted worse than water from other fountains in the school.

These examples of inquiry-based science not only provide more motivation for students but also reflect better the spirit of scientific inquiry. The increased motivation often comes from a feeling of ownership that derives from the investment that students make in designing and carrying out their experiments. Once in this state of mind it is not difficult to initiate students to the explanatory and predictive power of science.

Reforming the Commercial Publishing Behemoth

It is difficult to convince an industry that is making considerable profits that their products are inferior. Another vicious cycle appears to be at work in the commercial textbook publishing establishment. Teachers need textbooks to teach, and they naturally feel comfortable teaching from textbooks that are similar to those that they used when they were in school. Commercial publishers fill a void by providing teachers with glitzier versions of the old textbooks, which now include a teacher's edition and accompanying tests cued to the chapters in the textbook. This cycle is difficult to break. Those interested in deviating from traditional ways by writing a textbook that covers fewer topics in depth, and that provides teachers with information both on students' thinking and on instructional strategies are likely to be disappointed. Publishers are likely to reject the proposed textbook as being too radically different from those best-selling traditional textbooks that school systems buy.

To break this cycle will require efforts on several fronts. First, scientists, cognitive scientists, and teachers need to collaborate in developing prototype textbooks to serve as exemplars. These exemplars should cover less content in more depth, have a well thought out pedagogical progression, contain discussions for teachers on students' ways of thinking with justifications for the importance of probing and monitoring students' thinking, provide suggestions for helping students organize their knowledge hierarchically, promote the integration of concepts in problem solving-instruction, provide examples of assessment instruments that probe students' understanding of scientific concepts, provide examples of inquiry activities that illustrate the scientific paradigm, and provide suggestions of instructional strategies that are consistent with constructivist epistemology. Cadres of teachers need to be educated in the use of the new exemplars, education that must integrate the three types of knowledge discussed above. These teachers would return to their school systems and serve as resources to other teachers.

This model, in turn, requires changes in the educational, scientific, and commercial publishing sectors. States and school systems must demand that the curriculum materials used for instruction reflect a process-oriented approach that focuses on depth of understanding rather than superficial coverage of science facts. For example, the state of California has significantly impacted the commercial publishing sector by writing process-oriented curricular guidelines (California Department of Education, 1990) that textbooks or other instructional materials must satisfy before they can be adopted for use in the state. School systems must also provide time for teachers to discuss instructional innovation among themselves and to receive adequate in-service education. In addition, scientists need to become more involved in educational reform. Finally, commercial publishers must resist the "cloning method" for developing textbooks and take the initiative in developing instructional materials that reflect cognitive research findings in learning and instruction. These types of changes not only would provide students with instruction and curricula that are consistent with our current understanding of human cognition, but also would ensure that in-service teachers receive on-the-job education in the three types of knowledges needed for effective strategic instruction.

Reforming Student Assessment Practices

If we agree with the premises that "you get what you assess and you don't get what you don't assess," then perhaps the most efficacious way of reforming science education is to design tests toward which we would like educators to teach (Resnick & Resnick, 1992). This is, in fact, the approach being taken in *America 2000*. Taking cognizance of the fact that tests tend to drive the curriculum, the administration's blueprint for reform calls for a national assessment system that will set the tone for what will be taught in the schools. The recently formed National Council on Standards and Testing has endorsed the notion of a national assessment system and advocates the construction of high academic standards at the national level that are tied to the proposed assessments.

The types of assessments that are being proposed consist of "performance assessments" and "portfolio assessments" (Resnick & Resnick, 1992). Performance assessments can be thought of as direct evaluations of competence in complex tasks, rather than indirect evaluations that decompose and decontextualize complex tasks into seemingly unrelated sub-tasks. Portfolio assessments consist of collections of a students' work over a period of time. In science, a portfolio might consist of a science project or experiment that a student performed over months or perhaps even years.

To summarize, the types of student assessments being proposed in the current reform movement would reflect more closely the types of problems and questions that scientists consider during the course of "doing science." If the actual science assessments that will eventually emerge do in fact reflect scientists' view of science, then tests driving the curriculum will become a desideratum rather than a practice to be eradicated.

Concluding Remarks

I hope to have left the reader with several impressions. First, learning is a complex process that is constructed by individual learners. Although cognitive science has provided us with many insights into the learning process, the field is relatively young, and much remains to be done. Second, today's teachers should not just consider themselves teachers but also students of learning. The new breed of teachers not only needs to be knowledgeable in different areas, but also needs to be a life-long learner. Yesterday's notion that "anybody can teach" is a dead notion today. Finally, reforming the educational establishment requires a long-term, sustained effort on several fronts. Sporadic forays on specific fronts will not result in systematic, sustained changes.

It is also becoming clear that reform, whether it be in curriculum or test development or in the design of strategic instruction, needs the involvement and cooperation of scientists, teachers, cognitive scientists, and commercial publishers. The success of the current reform movement will depend on how well these groups pool their wisdom and talents in devising innovative solutions. Scientists should provide accurate scientific knowledge and insights on problem solving, teachers should provide expertise about children and about the culture of the classroom, cognitive scientists should provide insights on learning and instruction, and commercial publishers should reflect our current understanding about learning and instruction in their products. Only if such collaborations can be effected will science curricula, achievement tests, and instruction in scientific concepts and in problem solving reflect a coherent view.

I would like to close with a quote from T.S. Eliot's *Choruses from the Rock* that captures the essence of the message in

this chapter:

Where is the wisdom we have lost in knowledge?
Where is the knowledge we have lost in information?

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